NATIONAL ADVISORY COMMITTEE
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TECHNICAL NOTE

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INITIAL INVESTIGATION OF CARBIDE-TYPE CERAMAL OF 80-PERCENT TITANIUM CARBIDE PLUS 20-PERCENT COBALT FOR USE AS GAS-TURBINE-BLADE MATERIAL

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SUMMARY

An investigation was conducted to determine the material problems arising in the use of a carbide-type ceramal for gas-turbine blades. Specimens of an 80-percent titanium carbide plus 20-percent cobalt (by weight) ceramal were investigated for short-time tensile-strength characteristics at 1800° and 2200° F and for thermal-shock characteristics at 1800°, 2000°, 2200°, and 2400° F. Gas-turbine blades of this material were operated in a quasi-service-evaluation unit. The conditions of operation were indicated inlet-gas temperatures between 1700° and 2200° F and turbine tip speeds between 478 and 835 feet per second. A commercial tensile machine, a specially designed furnace and air-quench-chamber apparatus, and a small gas turbine were used for these investigations. X-ray-diffraction studies were made of the material before and after operation in the form of turbine blades. For comparison purposes, zircon and titanium carbide ceramics and an alloy were investigated for thermal-shock characteristics and turbine-blade performance, respectively.

The ceramal had a short-time tensile strength of 33,200 pounds per square inch at 1800° F and as high as 13,200 pounds per square inch at 2200° F. On a strength-to-weight basis, this ceramal was, in general, superior to alloys and ceramics. The ceramal survived 25 thermal-shock cycles at a temperature of 1800° F, 25 cycles at 2000° F, 25 cycles at 2200° F, and 25 cycles at 2400° F, whereas the zircon ceramic survived 1 cycle at 1800° F and the titanium carbide ceramic survived through 21 cycles at 2400° F.

Three ceramal blades survived 9 hours and 42 minutes of quasi-service evaluation, whereas six of the twelve original metal blades remained; at this time, one ceramal blade was accidentally broken. At 12 hours and 13 minutes, two of the three ceramal blades remained, whereas four metal blades remained. At this time, a second ceramal blade had been destroyed because of wheel-dovetail failure and the third ceramal blade failed as a result of service operation.

Examination by X-ray diffraction revealed that during operation a scale consisting of two layers formed on the ceramal blades. The outer layer was mainly titanium dioxide TiO_2 (rutile). The inner layer consisted mainly of cobalt titanate $CoTiO_3$. No significant change in the base material was indicated.

The investigation further yielded data, which indicated that:

(a) More care should be exercised in the handling of blades made of carbide ceramals than is customary with metal blades.

(b) Blades of carbide-type ceramals, having high thermal conductivities, cause the turbine-disk rim to run hotter than do metal blades.

(c) For long-time operation, coatings will be required on carbide-type ceramal blades for protection against oxidation if the naturally formed oxide coating is not protective.

INTRODUCTION

The current service life of metal turbine blades is relatively short at operating gas temperatures above 1800° F, and the ultimate operating temperature of such blades is limited by the melting point of their lowest melting constituent, which generally lies between 2300° and 2500° F. Research on materials for gas-turbine blades is guided by the following immediate goals: longer life at the relatively low gas temperatures of 1500° to 1800° F, a practical life at temperatures of 1800° to 2600° F, and a short but useful life at temperatures above 2600° F. These objectives necessitate research on materials having better high-temperature characteristics than those of metal alloys currently available. Research has led to a consideration of ceramic materials as a possible substitute; however, ceramic materials are at present poor in thermal-shock properties (the ability to withstand severe and abrupt temperature fluctuations of the surrounding gas). Some aspects of research in the field of ceramics are discussed in reference 1. The possibility of supplementing the desirable characteristics of a ceramic with the thermal-shock resistance of a metal suggests a composite material consisting of ceramic and metallic constituents that would result in a material of long life at high temperatures. Such materials have been termed "ceramals" (references 2 and 3). If the combinations and proportions of constituents in such materials are varied, some control over the properties of the material should be possible.

Ceramal bodies are not new, but have been suggested, in part, by the development of cemented carbides, which have been widely used for a number of years in the tool industry. The good strength at red heat, compared with metals, combined with extreme hardness made cemented carbides well suited for cutting tools. A large amount of research has been conducted towards obtaining fundamental data on cemented-carbide constituents in order to develop superior compositions. Fundamental data on a number of cemented-carbide constituents are given in reference 4.

An extremely important study has been the development of fabrication techniques because the characteristics of the ceramal are highly dependent upon the method of fabrication. Considerable information relative to the preparation of carbide powders and the fabrication of cemented carbides is contained in several United States patents. (For example, see reference 5.) This background in the fabrication of cemented carbides for tool applications aided in producing sound specimens for evaluation without embarking on a program of development in the laboratory. The earliest research on ceramals for gas turbines was conducted in Germany (reference 6).

A material having the characteristics of high thermal conductivity, high tensile strength, low thermal expansion, and low modulus of elasticity would be expected to possess high thermal-shock resistance. Reference 2 indicates for a ceramal consisting of 80-percent titanium carbide and 20-percent cobalt (by weight) a relatively high thermal conductivity (20.56 Btu/(hr)(sq ft)($^{\circ}$F/ft)), a high tensile strength, a low thermal expansion (5.0×10^{-6} (in./in.)/$^{\circ}$F), a modulus of elasticity of 55,000,000 pounds per square inch, and good tensile strength, from which the thermal-shock resistance was concluded to be adequate for turbine-blade use. A favorable strength-to-weight ratio is also indicated in reference 2.

An investigation was conducted at the NACA Lewis laboratory to determine experimentally the resistance to thermal shock and the short-time tensile strength at elevated temperatures of a carbide-type ceramal and the performance characteristics of the carbide-type ceramal blades operated under quasi-service conditions.

The particular determinations made were:

(a) Short-time tensile strength at 1800° and 2200° F

(b) Thermal-shock resistance at 1800°, 2000°, 2200°, and 2400° F

(c) Quasi-service performance characteristics of turbine blades operated at shaft speeds between 10,000 and 17,500 rpm (tip speeds of 478 and 835 ft/sec) and indicated inlet-gas temperatures between 1700° and 2200° F

Changes in the structure of the material resulting from operation as a turbine blade were investigated by X-ray diffraction.

All ceramal bodies used in this investigation were fabricated by Kennametal, Inc., who collaborated with the NACA by making available their extensive experience in the fabrication of ceramals.

APPARATUS AND PROCEDURE

Tensile-Strength Evaluation

The elevated-temperature, short-time, tensile-strength-evaluation apparatus consisted essentially of a commercial tensile machine fitted with a helium-atmosphere furnace (fig. 1). The 16,000-pound range of the tensile machine was used. Minimum dial graduation was 20 pounds. The machine was equipped with a hydraulic loading system that permitted constant rate of application of load. A platinum-wound electric furnace was used. The furnace was installed on the machine in such a manner that it could be conveniently manipulated and located about the specimen. A thermocouple attached to the specimen, by use of a wire wrapped around the specimen and the thermocouple, indicated specimen temperature. A second thermocouple near the furnace windings and connected to a temperature-control system so controlled the furnace as to maintain the specimen at the evaluation temperature. Platinum - platinum-13-percent-rhodium thermocouples were used. The helium atmosphere was used to minimize any oxidation effects upon the tensile-strength evaluations. Adapter rods and grips of high-temperature alloys were used to transmit load to the specimen. Ball-and-socket joints incorporated into the adapter rods were used to secure alinement and to obtain collinearity of specimen and load (fig. 1).

The specimens were inspected for internal and external flaws by radiographic and fluorescent-oil methods, respectively. Radiographic inspection revealed fine chemical segregation in these specimens. The segregation was not considered serious.

The ends of the specimens were wrapped with a single layer of woven asbestos sheet (fig. 2), which was secured with an adhesive. This wrapping was used to compensate for any distortion of the grips and any minute surface irregularities of the specimens. The adapter rods and the grips were then installed on the tensile machine and a tensile specimen was placed in the grips and the furnace positioned about the specimen. A load of 3000 pounds per square inch was applied to the specimen and alinement was secured by tapping gently on the rod and grips until misalinement, indicated by wire strain gages mounted on the specimen (fig. 2), was below 20 percent, which was considered satisfactory. The load was then reduced to 1000 pounds per square inch.

The furnace temperature was raised to 100° F above the evaluation temperature and the specimen was allowed to soak in helium atmosphere for approximately $12\frac{1}{2}$ hours while being subjected to the load of 1000 pounds per square inch in order to improve alinement and to relieve local stresses. This period of soaking was subsequently changed to 4 hours. During soaking, the nominal load of 1000 ± 100 pounds per square inch was maintained by the hydraulic loading system of the tensile machine. Upon completion of the soaking period, the temperature was lowered to the evaluation temperature within approximately 1/2 hour and the load increased at the rate of 2000 pounds per square inch per minute until the specimen fractured. The loading rate conformed to recommendations of reference 7. Specimen temperature was maintained within ±10° F.

Thermal-Shock Evaluation

Apparatus for the thermal-shock evaluation consisted of an electric furnace employing nonmetallic resistor bars to heat the specimen and an air-quenching system to cool the specimen. The specimens investigated were 1/4-inch-thick disks, 2 inches in diameter. Figure 3 shows the thermal-shock evaluation unit, which was so arranged that the specimen after heating could be moved directly into a stream of quenching air. Holders made of high-temperature alloys (fig. 4) were used to support and to transport the specimens from the furnace to the air-quenching stream. A glass window in the air-quenching chamber allowed observation of the specimen during the cooling portion of the test cycle.

Temperature of the furnace was measured by a thermocouple connected to a potentiometer and controlled by a second thermocouple connected to an electric temperature-control system. Chromel-alumel thermocouples were used up to 2200° F. Platinum - platinum-13-percent-rhodium thermocouples were used above 2200° F.

The specimens were inspected for internal and external flaws by radiographic and fluorescent-oil methods, respectively. Radiographic inspection revealed fine chemical segregation, which was not considered serious.

A specimen was placed in the holder and located in the preheated furnace where it was maintained at the evaluation temperature for 10 minutes, after which it was removed to the quenching-air stream within $\frac{1}{2}$ to $1\frac{1}{2}$ seconds and kept there for 5 minutes. The specimens were so placed in the air stream that the flat surfaces were parallel to the flow of air. The quenching air supplied at 85° F flowed at the rate of 50 pounds per minute through a 6-inch-diameter pipe with a velocity of approximately 50 feet per second. Preliminary studies with a thermocouple embedded in a ceramic specimen indicated that with the furnace at 1800° F this procedure resulted in an initial heating rate at the center of the specimen of 140° F per second and an initial cooling rate of 200° F per second. This heating and cooling operation constituted one cycle; the cycle was immediately repeated. While the furnace temperature was being established, the specimen was kept in the air chamber.

A specimen was subjected to 25 temperature cycles with a furnace temperature of 1800° F. If this treatment was successfully survived, 25 cycles were successively repeated with furnace temperatures of 2000°, 2200°, and 2400° F or until failure occurred. The appearance of a crack was considered to be a failure. In those cases in which oxidation occurred and a specimen was believed to have cracked, radiography was used to inspect the base material beneath the oxide surface. Upon completion of the investigation, all specimens were radiographically inspected for internal cracks if surface cracks were not apparent.

Quasi-Service Evaluation

A small gas turbine supplied with hot gases from a turbojet combustion chamber was used for the quasi-service evaluation of the ceramal blades. Gas temperature was measured upstream of the turbine inlet. This apparatus is described in detail in reference 8. This unit was modified by the addition of a 0.031-inch-thick, sheet-metal shield about the turbine, approximately 4 inches from the inner wall of the water-jacket housing. The space between the shield and the housing was filled with graphite asbestos sheet (fig. 5). This arrangement was used to prevent ricocheting fragments of fractured blades from injuring other blades and to preserve fragments. The wheel diameter was approximately 9.5 inches and the blades extended about 1.3 inches beyond the wheel. The wheel was dynamically balanced before it was installed in the turbine case and thereafter whenever rebalancing appeared necessary.

A typical ceramal gas-turbine blade is shown in figure 6. Metal blades obtained from the U. S. Air Force were used as control blades. These blades had the following nominal composition:

C	Ni	Fe	Cr	Mo	Co
0.15-0.35	1.75-3.25	0.5-2.0	25.5-29.5	5.0-6.0	Remainder

The inspection of all blades upon receipt for internal and external flaws by radiographic and fluorescent-oil methods, respectively, did not reveal any flaws.

The metal blades originally had shrouds. These shrouds were ground and faired into the airfoil-section contour so that the original blade length was preserved. This grinding was done to make the configuration of the metal blades the same as that of the ceramal blades; the ceramal blades had been made without a shroud in order to simplify fabrication. The blades were installed in a turbine disk that had been previously inspected by radiographic and fluorescent-oil methods.

The investigation required two phases, each resulting in a particular setup procedure:

Phase 1. - Three ceramal blades were installed at equal intervals about the disk and the remaining 139 dovetails were fitted with metal blades. The metal blades were installed in accordance with applicable U. S. Air Force technical orders. The ceramal blades were installed in a slightly different fashion; they had a root slightly narrower than the thickness of the disk, which allowed the disk material to be peened over the root, thereby locking the blade in place. Some peening was done on the roll-neck junction of the disk dovetail. The wheel was then so ground that all root protuberances of the metal blades were flush with the disk surfaces.

Phase 2. - Three ceramal blades were installed to replace the ones that failed during phase 1. The root sections of these three blades were plated with copper of approximately 0.01-inch thickness. The corresponding disk dovetails were enlarged to receive these blades. In addition, the radius of the dovetail junction at the roll and neck was increased. The fit was such that the copper just became scratched when a blade was installed. The wheel was peened only at the bottom of the root roll. The wheel at this stage is shown in figure 7. Twelve new metal blades were installed at equal intervals about the wheel periphery to serve as a control for the three new ceramal blades. Remaining in the wheel were 127 of the original metal blades. All unnecessary turbine-case components that were in the plane of wheel rotation or in the path of flying fragments were removed at this time.

The turbine was operated in the following manner for both phases. Combustion air was supplied, and the turbine was motored at approximately 6000 rpm for 5 minutes. The motoring was done in order to meet a safety requirement for a 5-minute preoperation scavenge (motor time). Combustion was then initiated and test conditions attained in approximately 3 minutes (power time). The wheel was then operated at required conditions (condition time) until a blade failure occurred. Speed was maintained within ±200 rpm and temperature within $\pm 15^{\circ}$ F. Failure was indicated by a change in pitch of sound from the unit. Upon failure, combustion was discontinued and air flow was reduced to a value at which the turbine motored at approximately 6000 rpm. This flow was maintained for approximately 10 minutes in order to cool the assembly and the turbine was then removed for overhaul.

All fractured blades were removed and replaced with new metal blades. All severely cracked metal blades were considered to be failures and were replaced; this replacement was made because failure in this instance was imminent and the blades were, for practical purposes, fractured; additional complete failures would result in more shutdowns and also increase the risk of a flying fragment injuring sound blades. All metal replacement blades were installed in accordance with applicable U. S. Air Force technical orders.

Records were kept of operating conditions and of blade condition at each overhaul.

X-Ray-Diffraction Study

Comparison of the structure of the material as received and after operation was made by X-ray-diffraction studies. Debye-Scherrer powder cameras, 114.6 and 143.2 millimeters in diameter, were used with filtered cobalt and copper radiations in obtaining diffraction patterns of the ceramal in the "as-received" condition and of ceramal blades after failure in the quasi-service investigation. Identification of components was made by comparing spacings of the pattern obtained with the interplanar spacing of compounds of the various elements listed in the literature and in the A.S.T.M. card index.

RESULTS AND DISCUSSION

Tensile-Strength Evaluation

The results obtained in the short-time tensile-strength evaluation of the ceramal at 1800° and 2200° F are presented in table I. At 1800° F, the average short-time tensile strength obtained with specimens 3D1 and 3D5 was 33,200 pounds per square inch based upon the original test-section area. Specimen 3D1 underwent negligible oxidation; specimen 3D5 underwent a 0.2-percent reduction in area because of oxidation, which can also be considered negligible. Specimen 3D2 yielded a short-time tensile strength of 7800 pounds per square inch at 2200° F. This specimen, however, underwent a 12-percent reduction in area because of oxidation subsequent to a failure of supply of the helium atmosphere. On the assumption that practically all the oxidation occurred during the soaking period, the tensile evaluation was in reality conducted upon a specimen test-section area of 0.1712 square inch (measured after removal of oxide film) rather than of the 0.1955-square-inch original test-section area. The oxide scale was not considered as possessing any significant load-carrying capacity and therefore was not considered in determining fracture stresses. Correction for this change in area gave a tensile strength of 8900 pounds per square inch at 2200° F.

Specimen 3D3 failed during the soaking period. Specimen 3D4 was soaked 4 hours at 2300° F and yielded a short-time tensile strength of 12,000 pounds per square inch at 2200° F. Correction for oxidation gave a tensile strength of 13,200 pounds per square inch at 2200° F. The assumption was made that the 4-hour soaking at 2300° F used for specimen 3D4 would result in adequate alinement and stress relieving and would minimize any detrimental effects of the longer soaking and would thereby result in a more reliable short-time tensile-stress value. These tensile investigations had the features of a stress-rupture test; in particular, specimen 3D2 was subjected to a load of 1000 pounds per square inch for $13\frac{1}{2}$ hours at 2300° F and specimen 3D4 was subjected to a load of 1000 pounds per square inch for 4 hours at 2300° F. No data are available for alloys with which to compare these stress-rupture values.

The short-time tensile strength of 33,200 pounds per square inch at 1800° F compares favorably with that of the heat-resistant alloys commonly used. These alloys have a short-time tensile strength as great as 37,800 pounds per square inch for alloy 422-19 at 1800° F as indicated in reference 9 . In general, the short-time tensile strength for high-temperature alloys is about 33,000 pounds per square inch at 1800° F. Reference 1 indicates that National Bureau of Standards Body 4811 has a short-time tensile strength of 19,000 pounds per square inch at 1800° F. At 2200° F, there are few short-time tensile data for the metal alloys or for ceramics with which the ceramal tensile strengths of 8900 and 13,200 pounds per square inch compared. This value can be considered good at temperatures approaching the melting points of metal alloys. Figure 8 shows specimen 3D5 after failure and illustrates a fracture typical of a brittle material.

When densities of 5.5 (reference 2), 3.0 (reference 1), and 8.3 (reference 9) grams per cubic centimeter were used for the ceramal, the National Bureau of Standards Body 4811, and alloy 422-19, respectively, which yielded better than average strength-to-weight ratios for the ceramic and the metal, the strength-to-weight ratio of the ceramal at 1800° F is 0.95 times that of the ceramic and 1.3 times that of the alloy. Inasmuch as centrifugal forces are largely responsible for stresses in a turbine blade, the high strength-to-weight ratio of the ceramal compared with metals is of importance.

Thermal-Shock Evaluation

The results obtained in the thermal-shock evaluation are presented in table II. The ceramal survived 25 cycles at 2400° F, whereas a zircon ceramic survived one cycle at 1800° F. Data for the ceramic are included to enable a comparative evaluation using the same apparatus. Zircon is regarded as having good thermal-shock properties (reference 10). Titanium carbide was investigated to allow comparison of the thermal-shock characteristics of titanium carbide with titanium carbide plus cobalt. The addition of cobalt tends to improve the thermal-shock characteristics of the ceramic. The thermal-shock resistance of this ceramic is very good; specimen 3A7 survived 14 cycles at 2400° F and specimen 3A10 survived 21 cycles at 2400° F.

During the thermal-shock investigation, severity of oxidation of the ceramal specimens increased as evaluation temperatures progressed from 1800° to 2400° F. Upon completion of 25 cycles at 1800° F, a relatively thin, tight film was noted. Upon completion of the 25 cycles at 2400° F, the film had become scaly and more extensive, as indicated in figure 9. Apparently, a difference in coefficients of expansion of the film and of the base material together with the more severe thermal gradients at the higher temperatures cracked the film and exposed new surfaces to oxidation, resulting in this appearance. The film thickness at this time was determined as approximately 0.027 inch.

On the basis of this evaluation, it was concluded that the thermal-shock resistance of this ceramal is excellent, relative to currently available ceramics.

Quasi-Service Turbine-Blade Evaluation

Phase 1. - The results obtained in phase 1 are presented in table III, which shows that during this phase of the evaluation, one ceramal blade failed after 10 minutes of operation at 17,500 rpm and an indicated inlet gas temperature of 2000° F. The total time of operation was 4 hours and 40 minutes under the various conditions noted in table III. The remaining two ceramal blades used in phase 1 fractured within an additional 5 minutes of operation at the same conditions. Examination of the failures indicated that the blades fractured in the neck-roll junction at a point of possible stress concentration caused by the presence of both peening and an abrupt change in root configuration (fig. 10). During overhaul, after failure of the first ceramal blade, minute cracking was noted on the back side of one of the other ceramal blades at the neck-roll junction. This occurrence might reasonably have been the result of stress concentration. These three failures may also have been largely the result of

(1) operation at a shaft speed (17,500 rpm) that may have caused resonant vibration of the blade to occur

(2) peening stresses, in addition to the stresses existing at operating conditions at time of fracture, exceeding the strength of the material.

Phase 2. - The roots of a second set of three ceramal blades were copper-plated and then so installed as to permit redistribution of load and minimizing of stress-concentration effects. Copper was selected as a plating in order to preserve the full advantage of the excellent thermal conductivity of the ceramal (20.56 Btu/(hr)(sq ft)(°F/ft) at room temperature, reference 2). The metal blades had a substantially lower thermal conductivity (8.38 Btu/(hr)(sq ft)(°F/ft) at 392° F). The high thermal conductivity of the ceramal blade material was expected to result in lower operating temperatures for these blades and would increase operating temperatures of the disk rim by heat conduction to the disk. Of the 139 metal blades, 127 were original blades from phase 1, and 12 were new blades installed as control blades. The operation program was modified to eliminate wheel operation at or near 17,500 rpm.

The results obtained in phase 2 of this evaluation with the second set of ceramal blades are indicated in table IV, which shows that 12 hours and 13 minutes of operation were completed. At the end of this time, service failure had taken place in 96 metal blades from phase 1 of this investigation, 8 control blades (a ninth blade had begun to crack), 4 replacement, and 1 ceramal blade. Of the three ceramal blades, only one can be considered a service failure. One ceramal blade, which was inadvertently fractured during overhaul after 9 hours and 42 minutes of operation, is shown in figure 11 in which a two-layered oxide film is apparent. The fracture of this blade during routine wheel handling is indicative of the need for special care in the handling of bodies fabricated of materials of this type.

A second ceramal blade (fig. 12(a)) was destroyed after 12 hours and 13 minutes of operation because of wheel-dovetail failure that allowed the blade to fly loose. A study of figure 12(b) indicates distortion of disk material about the failed dovetail 33 minutes before failure. The ceramal blades were not removed to other positions because they were held very tightly and blade injury might result through moving. Enlargement of the dovetail roll, peening, and local heating of the disk because of the high thermal conductivity of the ceramal blade material undoubtedly resulted in a stress-temperature condition that caused fracture of the dovetail. The third ceramal blade apparently fractured as a result of factors normally operating to induce blade failure (fig. 13(a)), although the blade fractured simultaneously with the disk-dovetail failure.

During the course of operation, the copper flowed from the ceramal blade roots, which is also indicated in figure 12(b). This condition was noted shortly after the wheel was put into operation. The greater part of phase 2 of this investigation was conducted with the ceramal blades retained in the manner indicated. A thin layer of copper remained fused to the blades and to the wheel dovetail, retaining the blades in place. Stress at the root neck-roll junction was relieved. A ceramal blade (fig. 12(b)) was nicked; this nick occurred during run 3 and was caused either by a flying blade fragment or by foreign matter in the inlet gas.

The results of the quasi-service evaluation of the ceramal blades show that all three ceramal blades survived 9 hours and 42 minutes of operation at which time six of the original twelve control blades survived. Two of the three ceramal blades survived to 12 hours and 13 minutes of operation at which time a total of four control blades survived. In addition, four metal blades installed to replace original metal blades had fractured.

The replacement blade fractured during run 7 was one of 19 blades installed after run 5. The replacement blades that fractured during run 8 represented one blade each of samples of 6, 17, and 8 blades installed after runs 1, 3, and 6, respectively. Statistically, each of these particular blades is the poorest of its respective sample, and this fact must be realized in order to evaluate the significance of the failure of these four replacement blades. During phase 2 there were eight starts and eight shutdowns. During starting, the inlet-gas temperature was brought from room temperature to slightly under evaluation temperature within 30 seconds. Upon shutting down, combustion was abruptly terminated and air flow reduced slightly. Both operations produced thermal shock, which had no noticable effect upon the ceramal blades.

The fracture surface of the service-failed ceramal blade after 12 hours and 13 minutes of operation is shown in figure 13(b). A two-layered oxide film is in evidence. This film was found to be of different thickness on the leading and trailing edges of the blade, which might be indicative of the temperatures at those areas. The film thicknesses for this blade and for the blade inadvertently fractured after 9 hours and 42 minutes of operation are given in the following table:

Time to fracture		Leading-edge thickness (in.)	Trailing-edge thickness (in.)
(hr)	(min)		
9	42	0.0134	0.0035
12	13	.0223	.0163

These measurements were taken by use of a microscope fitted with a filar eyepiece, with the fractured surface of a blade viewed through the eyepiece. The scale was tenacious and showed no tendency to flake off during turbine operation. This type scale would tend to preserve aerodynamic shape and to minimize the risk of flying scale damaging sound blades. Expedients such as ceramic coating may be found necessary to minimize oxidation for long periods of operation. No appreciable elongation of the ceramal blades occurred.

X-Ray-Diffraction Study

The two layers of scale of a fractured blade specimen were examined. The outer layer was composed mainly of titanium dioxide TiO_2 (rutile). The inner layer was composed mainly of cobalt titanate $CoTiO_3$. The base material of the ceramal exhibited no significant change.

SUMMARY OF RESULTS

The investigations to determine characteristics of a carbide-type ceramal, strength at elevated temperatures, resistance to thermal shock, and performance characteristics when formed into a blade shape and operated under quasi-service conditions, gave the following results:

1. The short-time tensile strengths of 33,200 pounds per square inch at 1800° F and as high as 13,200 pounds per square inch at 2200° F of the particular carbide ceramal compared favorably with similar data for ceramics and currently used alloys. On a strength-to-weight basis, this ceramal was, in general, superior to alloys and ceramics.

2. The thermal-shock resistance of the ceramal was excellent compared with zircon ceramic and good compared with titanium carbide ceramic. The ceramal survived 25 thermal-shock cycles at 1800° F, 25 cycles at 2000° F, 25 cycles at 2200° F, and 25 cycles at 2400° F, whereas the zircon ceramic survived 1 cycle at 1800° F, and the titanium carbide ceramic survived 21 cycles at 2400° F.

3. The quasi-service turbine-blade evaluation using a sample of three ceramal blades and a sample of 12 metal blades resulted in the following data:

(a) At 9 hours and 42 minutes, three ceramal blades had survived whereas six of the metal blades remained; at this time, one ceramal blade was accidentally broken.

(b) At 12 hours and 13 minutes, two of the three ceramal blades remained, whereas a total of only four metal blades remained. At this time, a second ceramal blade had been destroyed because of disk-dovetail failure and the third blade failed in service.

4. During operation, a film consisting of two layers formed on the ceramal blades. The outer layer was mainly titanium dioxide TiO_2 (rutile). The inner layer consisted mainly of cobalt titanate $CoTiO_3$. No significant change occurred in the base material.

CONCLUDING REMARKS

The investigation yielded data from which it was indicated that:

1. More care should be exercised in the handling of blades made of carbide-type ceramals then is customary with blades of alloys.

2. Blades of carbide-type ceramals having high thermal conductivities cause the turbine disk rim to run hotter than do metal blades.

3. The scale is tenacious and tends to preserve aerodynamic shapes and to inhibit scaling under conditions of blade operation similar to those reported. For more severe operation, protective coatings against oxidation might be required.

4. The 80-percent titanium carbide plus 20-percent cobalt carbide-type ceramal shows promise for gas-turbine-blade application at relatively high temperatures for short times.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 6, 1948.

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TABLE I - SHORT-TIME TENSILE EVALUATION

1	2	3	4	5	6	7	8	9	10	11	
Specimen	Soaking time (hr)	Soaking temperature (°F)	Evaluation temperature (°F)	Breaking load (lb)	Specimen diameter at fracture point before test (in.)	Specimen area at fracture point[a] (sq in.)	Fracturing stress[a] (lb/sq in.)	Specimen diameter at fracture point after oxide-scale removal (in.)	Specimen area at fracture point[b] (sq in.)	Corrected fracturing stress[b] (lb/sq in.)	Remarks
3D1	$12\frac{1}{2}$	1900	1800	6240	0.5000	0.1963	31,800	0.5000	0.1963	31,800	Fluorescent-oil surface inspection, satisfactory. Radiograph, fine chemical segregation
3D2	$13\frac{1}{2}$	2300	2200	1525	.4990	.1955	7,800	.4670	.1712	8,900	Fluorescent-oil surface inspection, satisfactory. Radiograph, fine chemical segregation
3D3	--	--	--	--	.5000	--	--	--	--	--	Broke during soaking at 2300° F. Load, 200 pounds. Fluorescent-oil surface inspection, satisfactory. Radiograph, fine chemical segregation
3D4	4	2300	2200	2350	.4998	.1958	12,000	.4753	.1772	13,200	Fluorescent-oil surface inspection, satisfactory. Radiograph, fine chemical segregation
3D5	12	1900	1800	6820	.5016	.1975	34,600	.5010	.1970	34,600	Fluorescent-oil surface inspection, satisfactory. Radiograph, fine chemical segregation

[a]Calculated from diameter of column 6.
[b]Calculated from diameter of column 9.

TABLE II - THERMAL-SHOCK EVALUATION

[Radiography indicated fine chemical segregation in ceramal specimens, none in ceramic. No external flaws existed.]

Speci-men	Constituent	Weight (percent)	Cycles completed			
			1800° F	2000° F	2200° F	2400° F
3D13	Titanium carbide (TiC)	80				
	Cobalt (Co)	20	25	25	25	25
3D14	Titanium carbide (TiC)	80				
	Cobalt (Co)	20	25	25	25	25
7A10	Zircon ($ZrSiO_4$)	100	1	-------	-------	-------
3A7	Titanium carbide (TiC)	100	25	25	25	14
3A10	Titanium carbide (TiC)	100	25	25	25	21

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TABLE III - PHASE 1 OF QUASI-SERVICE TURBINE-BLADE EVALUATION

Run	Operating time		Cumulative operating time		Conditions			Metal blades cracked and replaced	Metal blades completely fractured	Total metal blades replaced	Cumulative total metal blades replaced	Ceramal blades fractured	Cumulative total ceramal blades fractured
					Shaft speed (rpm)	Tip speed (ft/sec)	Indicated inlet gas temperature (°F)						
	(hr)	(min)	(hr)	(min)									
		30		30	10,000	478	1750	0	0	0	0	0	0
		30	1		10,000	478	1800	0	0	0	0	0	0
		30	1	30	10,000	478	1850	0	0	0	0	0	0
1		30	2		10,000	478	1900	0	0	0	0	0	0
		30	2	30	10,000	478	1950	0	0	0	0	0	0
	1		3	30	10,000	478	2000	0	0	0	0	0	0
		30	4		12,500	596	2000	0	0	0	0	0	0
		30	4	30	15,000	716	2000	0	0	0	0	0	0
		10	4	40	17,500	835	2000	0	0	0	0	1	1
2		5	4	45	17,500	835	2000	0	0	0	0	2	3

TABLE IV - PHASE 2 OF QUASI-SERVICE TURBINE-BLADE EVALUATION

Run	Operating time		Cumulative operating time		Conditions			Metal blades cracked and replaced	Metal blades completely fractured and replaced	Total metal blades replaced	Cumulative total metal blades replaced	Cumulative total control-blades fractured	Ceramal blades fractured
	(hr)	(min)	(hr)	(min)	Shaft speed (rpm)	Tip speed (rpm)	Indicated inlet gas temperature (°F)						
1		30		30	10,000	478	1700						
		30	1		10,000	478	1800						
		30	1	30	10,000	478	1900						
		30	2		10,000	478	2000						
		30	2	30	10,000	478	2100		2 control				
	2		4	30	10,000	478	2200			6	6	2	
	1	30	6		12,500	596	2200		4 original				
2	1	30	7	30	12,500	596	2200						
		20	7	50	15,000	716	2200	8 original 1 control	4 original	13	19	3	
3		46	8	36	15,000	716	2200	13 original	4 original	17	36	3	
4		20	8	56	15,000	716	2200	6 original	2 original	8	44	3	
5		46	9	42	15,000	716	2200	9 original 3 control	7 original	19	63	6	1 broken during overhaul
6		55	10	37	15,000	716	2200	12 original 2 control	4 original	18	81	8	
7	1	3	11	40	15,000	716	2200	1 replacement (installed after run 5)	11 original	12	93	8	
8		33	12	13	15,000	716	2200	8 original 3 replacement (installed after runs 1, 3, and 6)	4 original	15	108	8	1 service failure 1 destroyed by dovetail failure in wheel

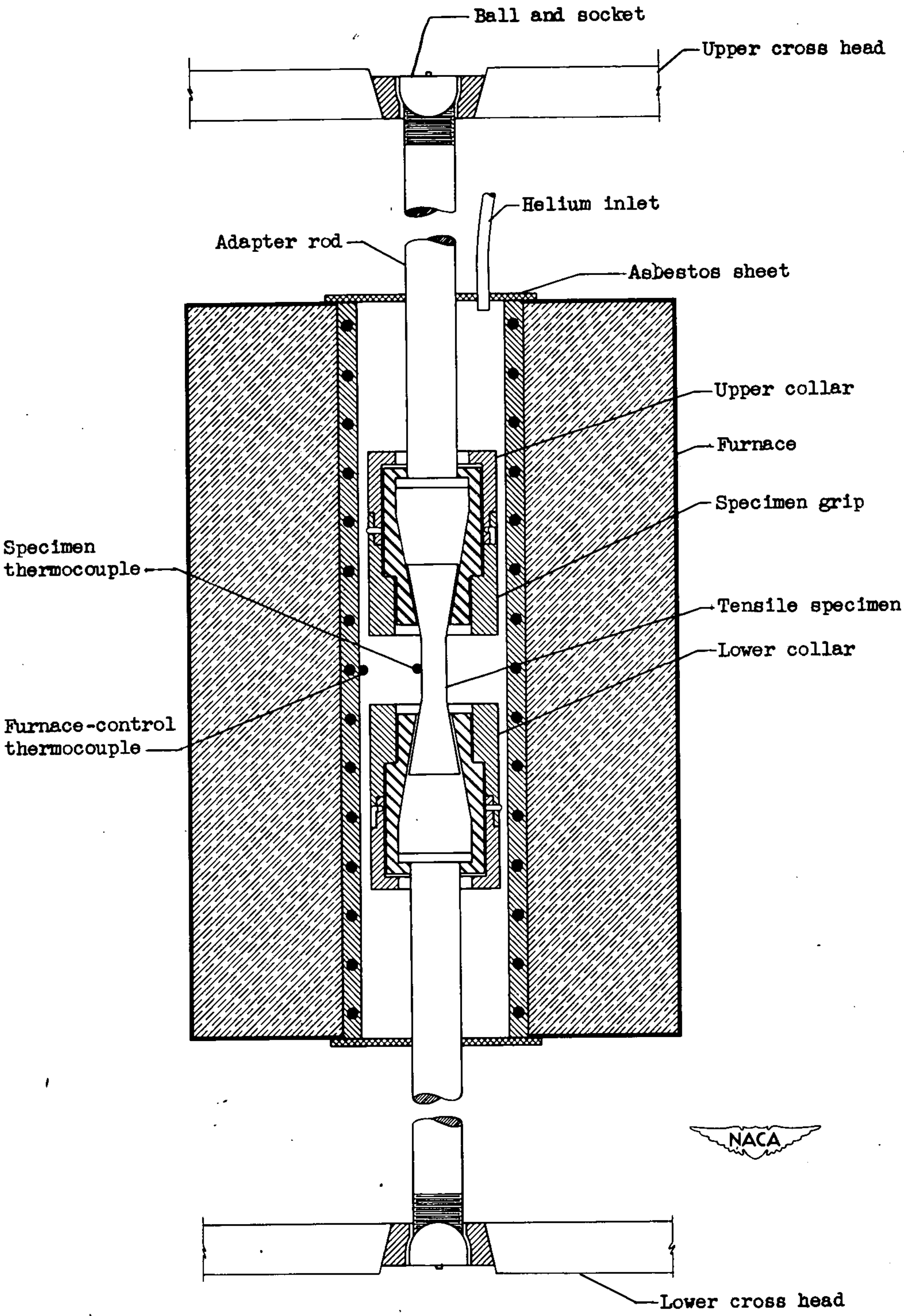

Figure 1. - Setup for tensile-strength evaluation.

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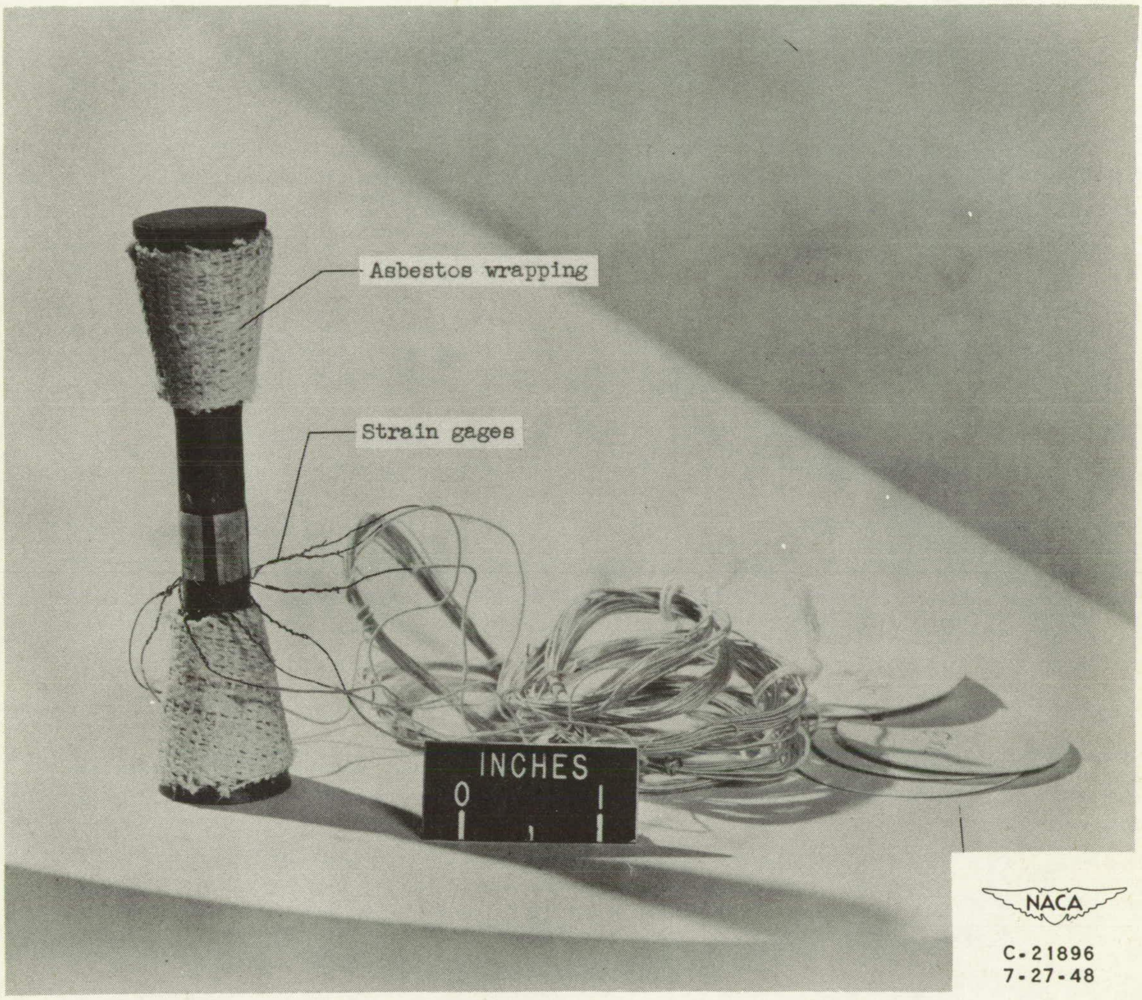

Figure 2. - Tensile specimen before investigation.

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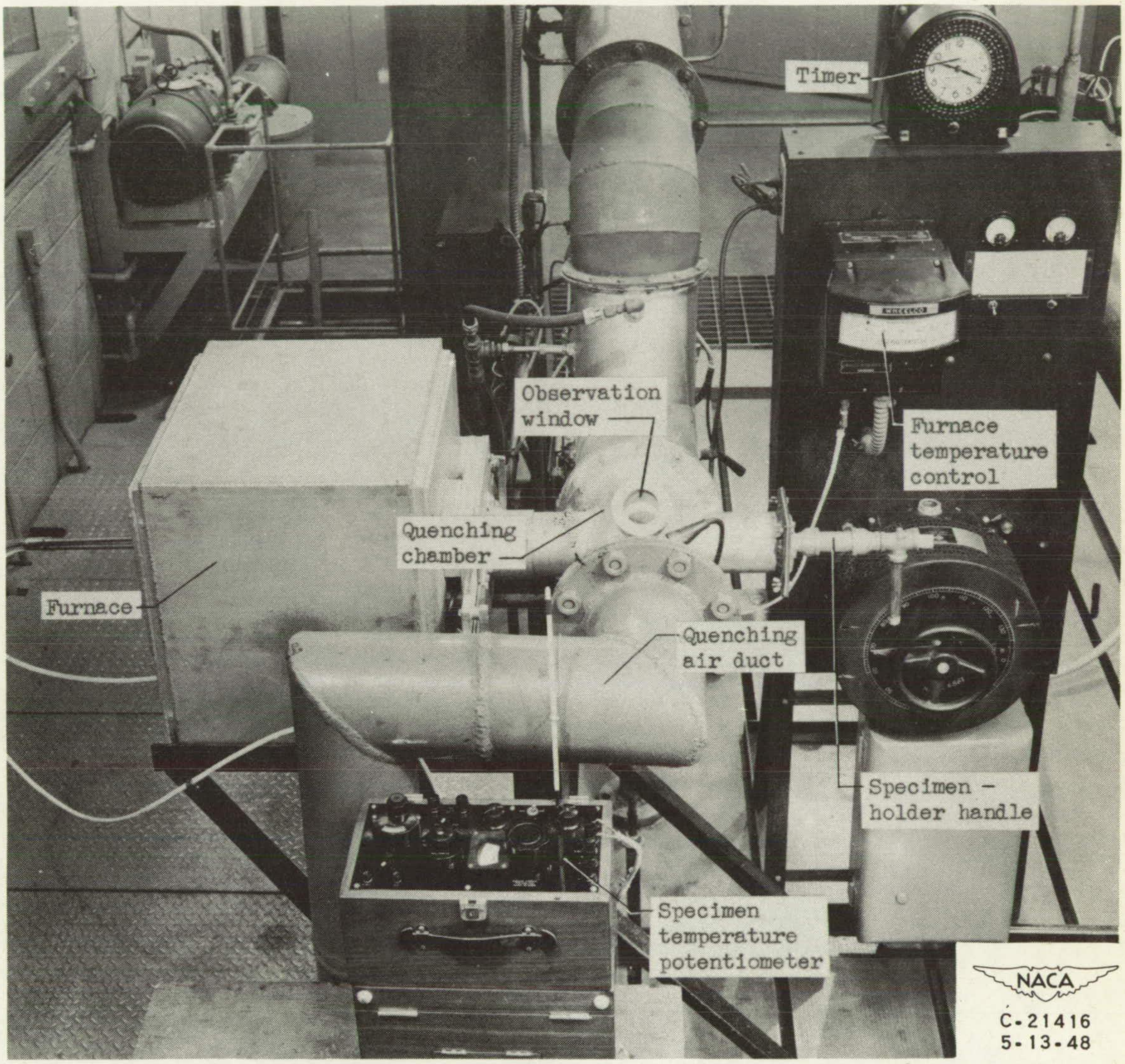

Figure 3. - Thermal-shock evaluation unit.

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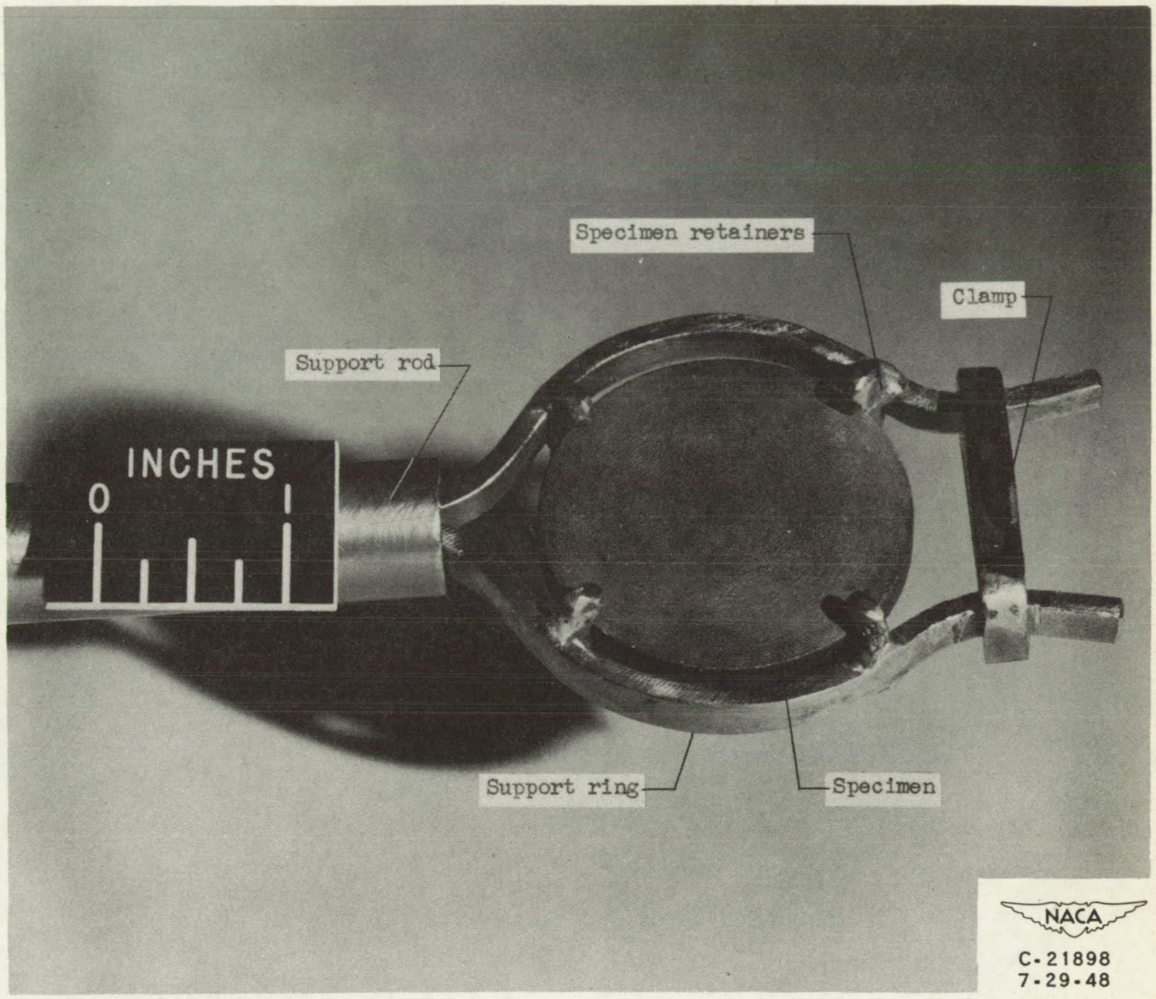

Figure 4. - Holder and specimen for thermal-shock evaluation. Specimen floats in retainers.

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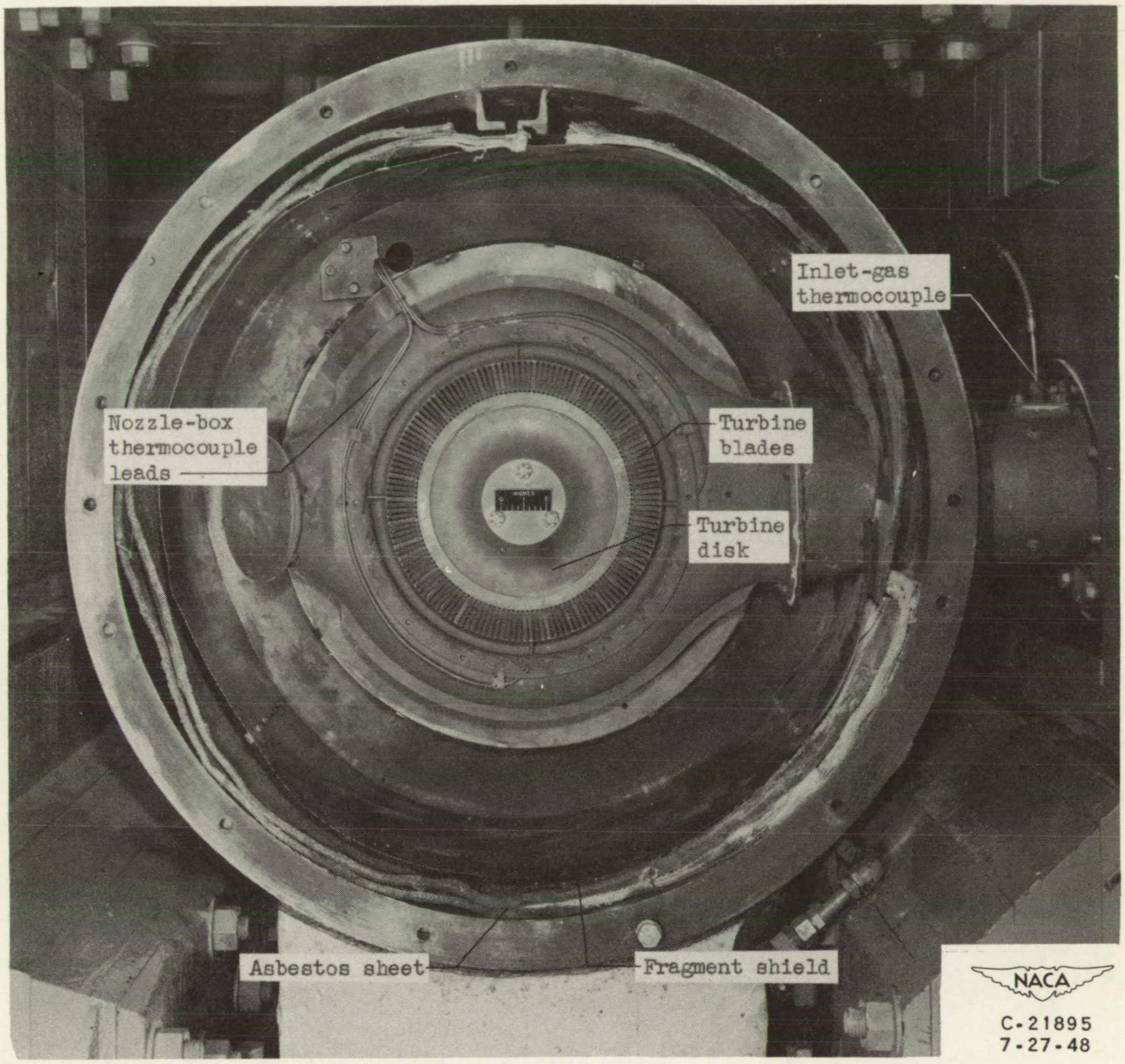

Figure 5. - Quasi-service evaluation unit showing shield and asbestos sheet used to preserve blade fragments.

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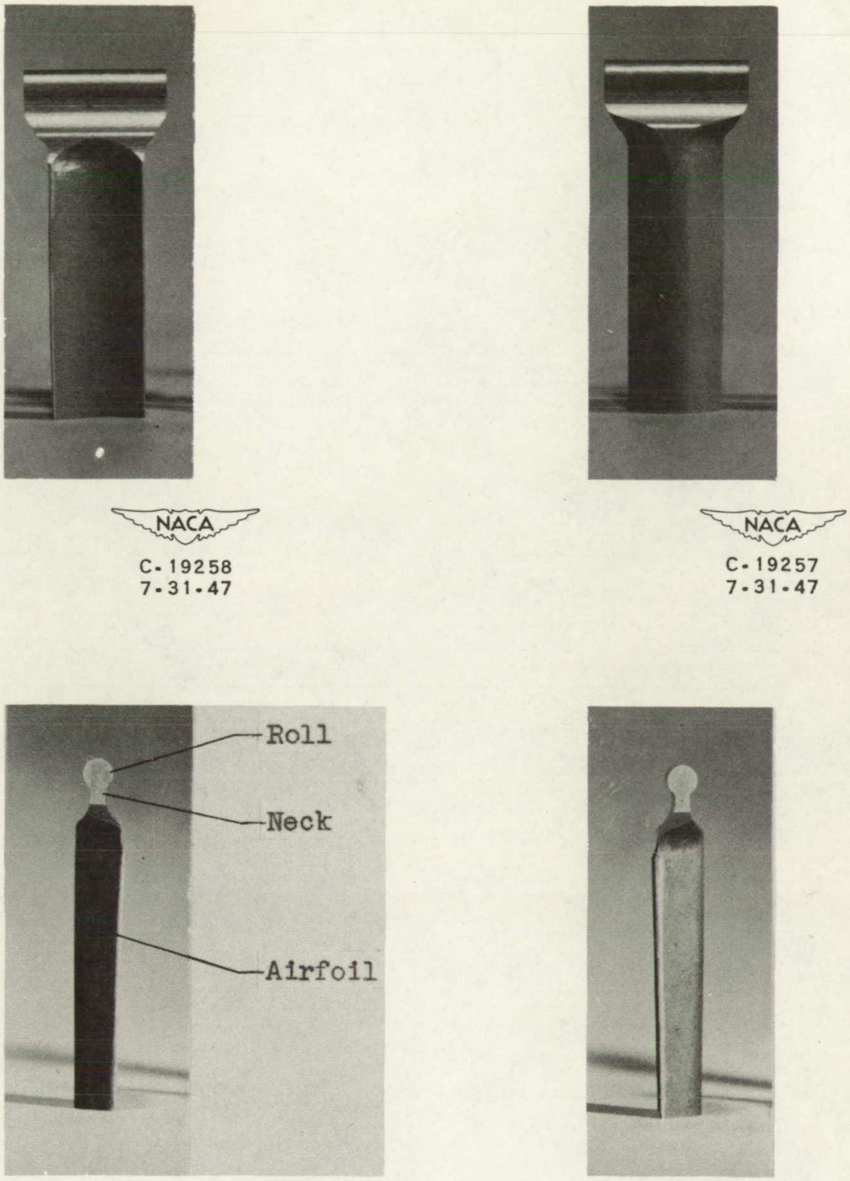

Figure 6. - Typical ceramal blade.

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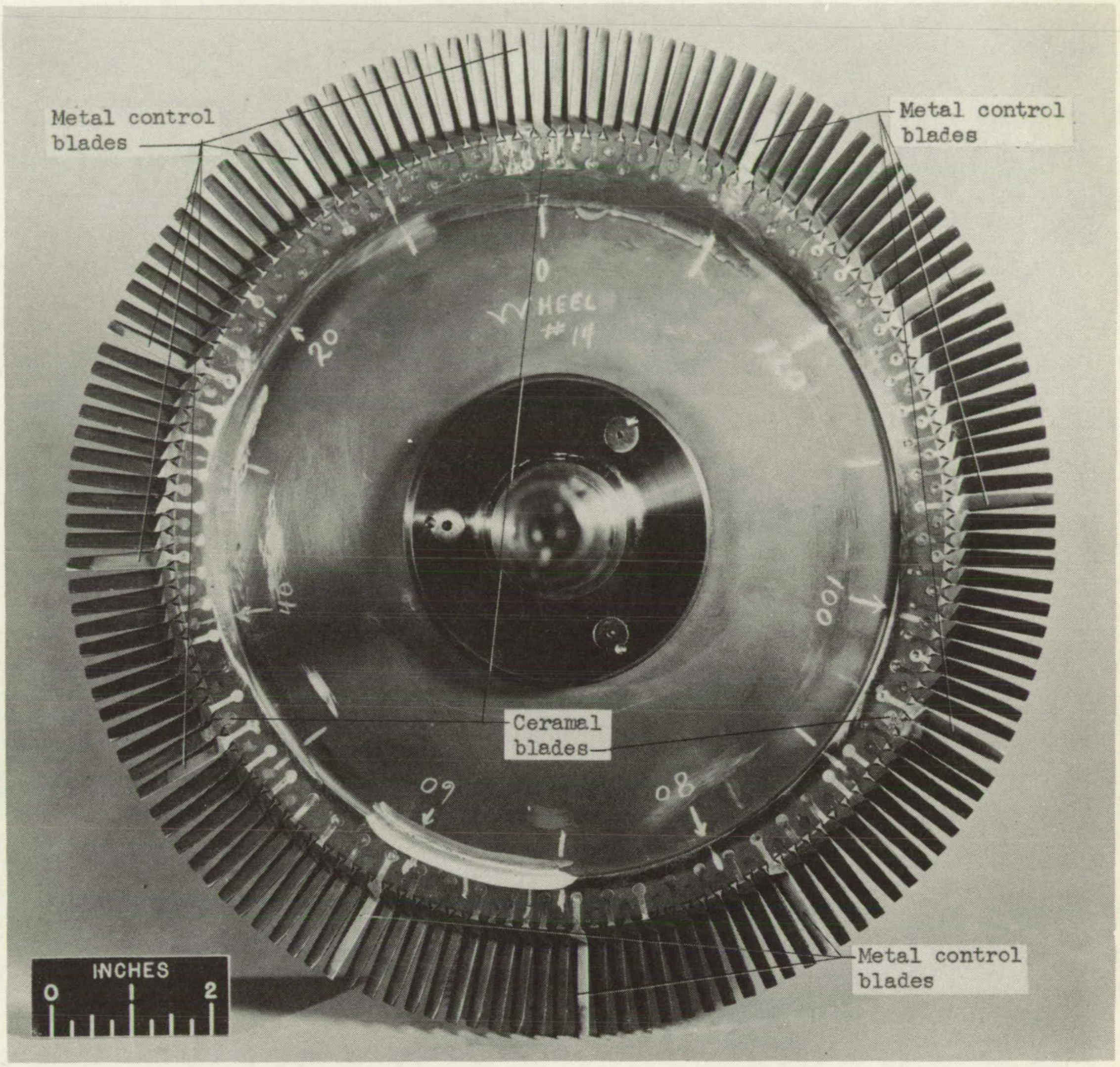

Figure 7. - Turbine-wheel assembly with ceramal blades before phase 2 of investigation. Upstream side.

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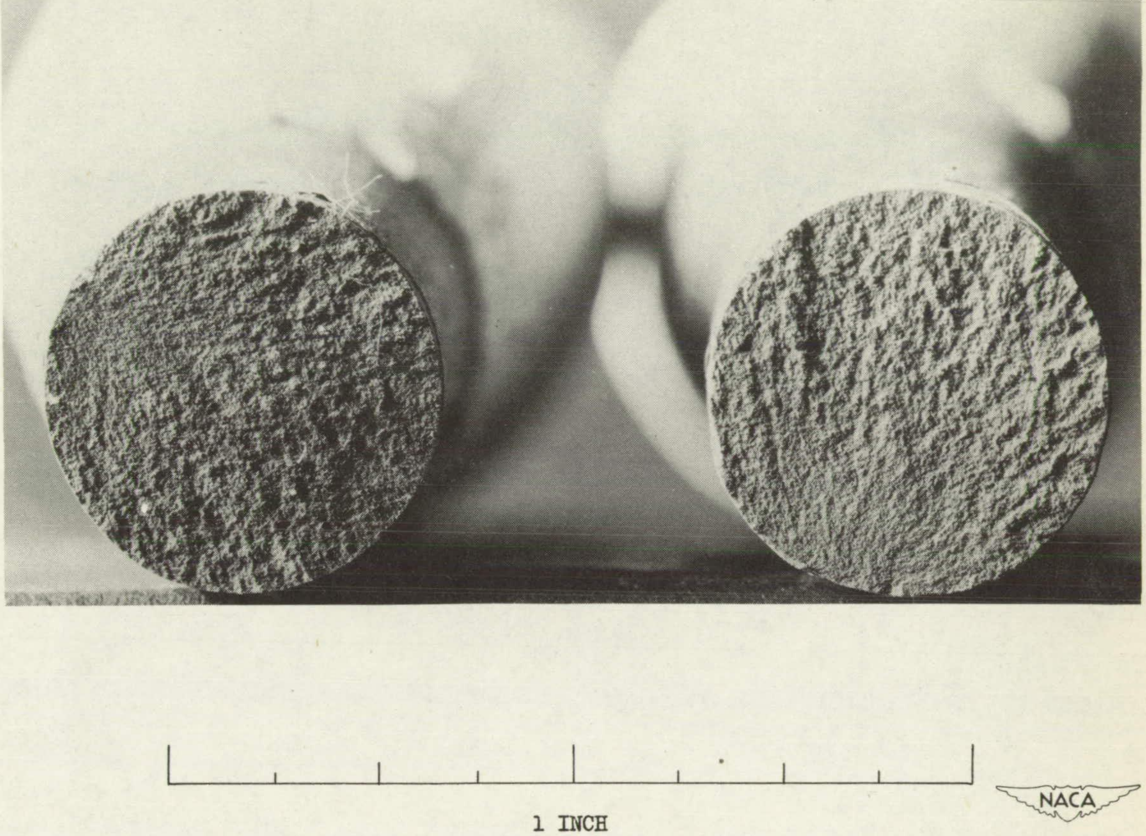

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Figure 8. - Fractured surface of ceramal tensile specimen 3D5. Tensile strength, 34,600 pounds per square inch at 1800° F.

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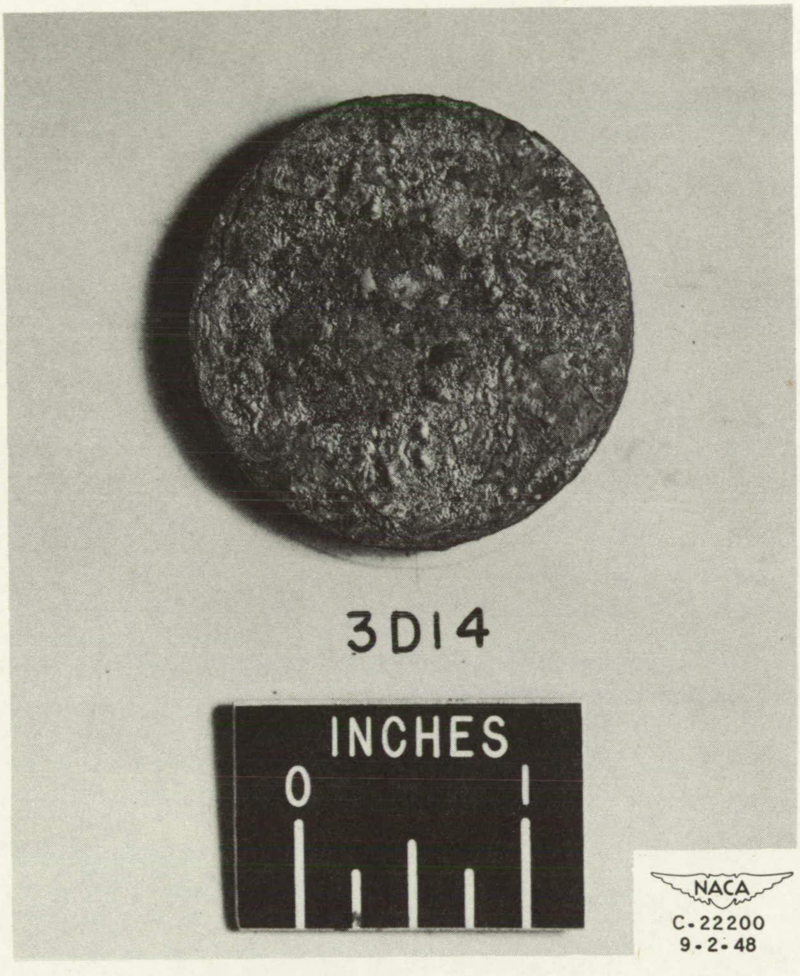

Figure 9. - Ceramal thermal-shock specimen after completion of 25 cycles at 1800°, 25 at 2000°, 25 at 2200°, and 25 at 2400° F.

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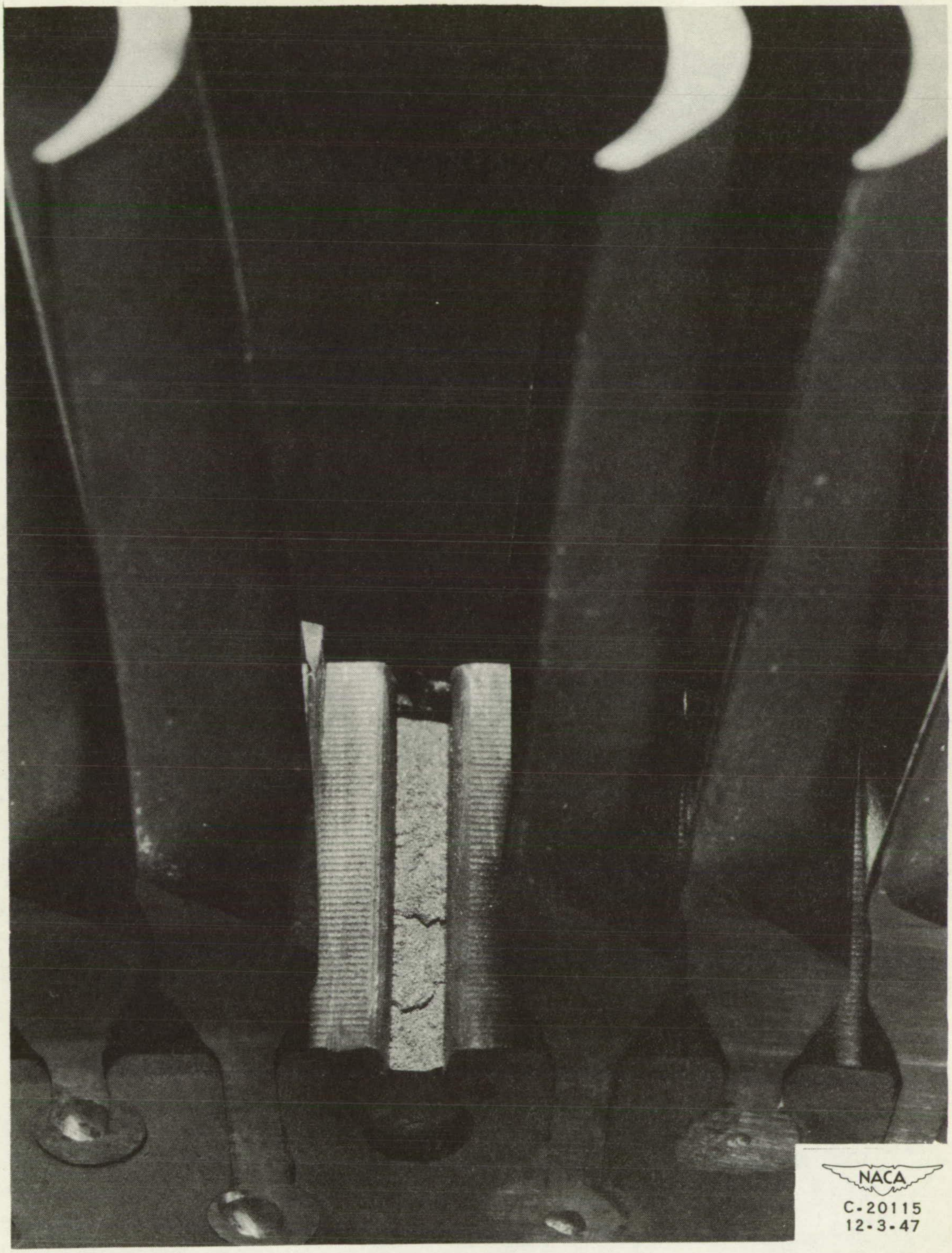

Figure 10. - Typical fracture of ceramal blade experienced during phase 1 of quasi-service evaluation.

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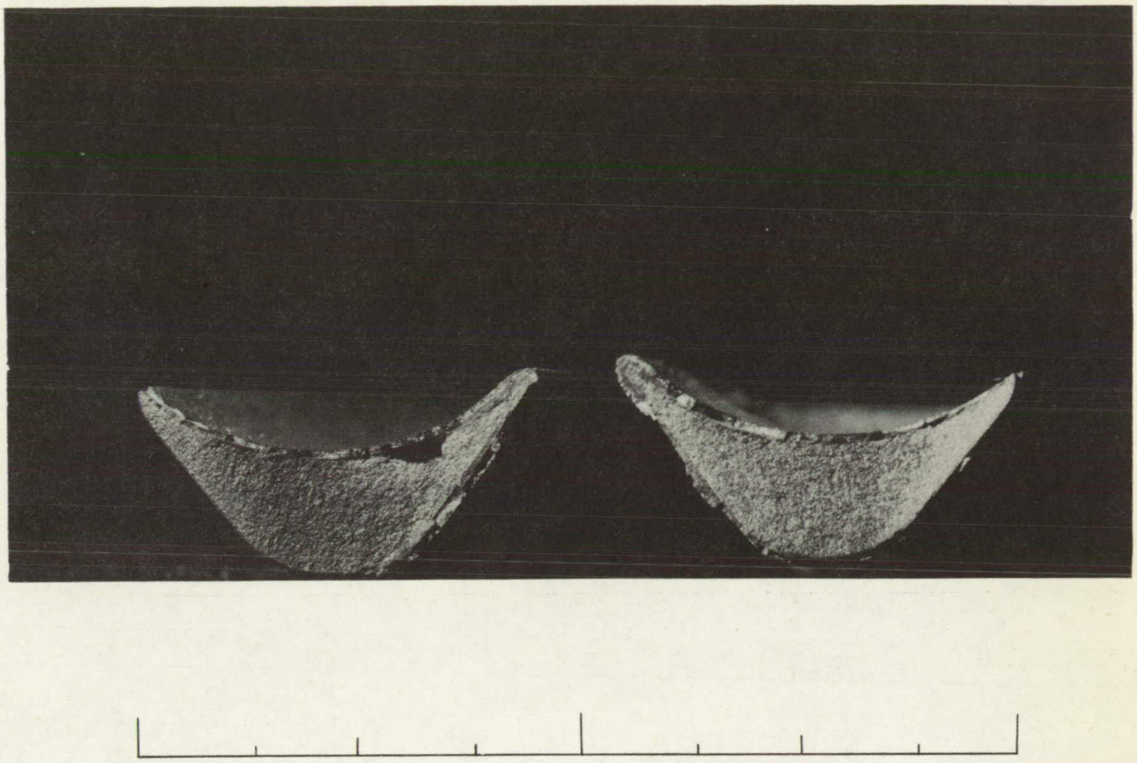

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Figure 11. - Ceramal blade inadvertently fractured after 9 hours and 42 minutes of operation.

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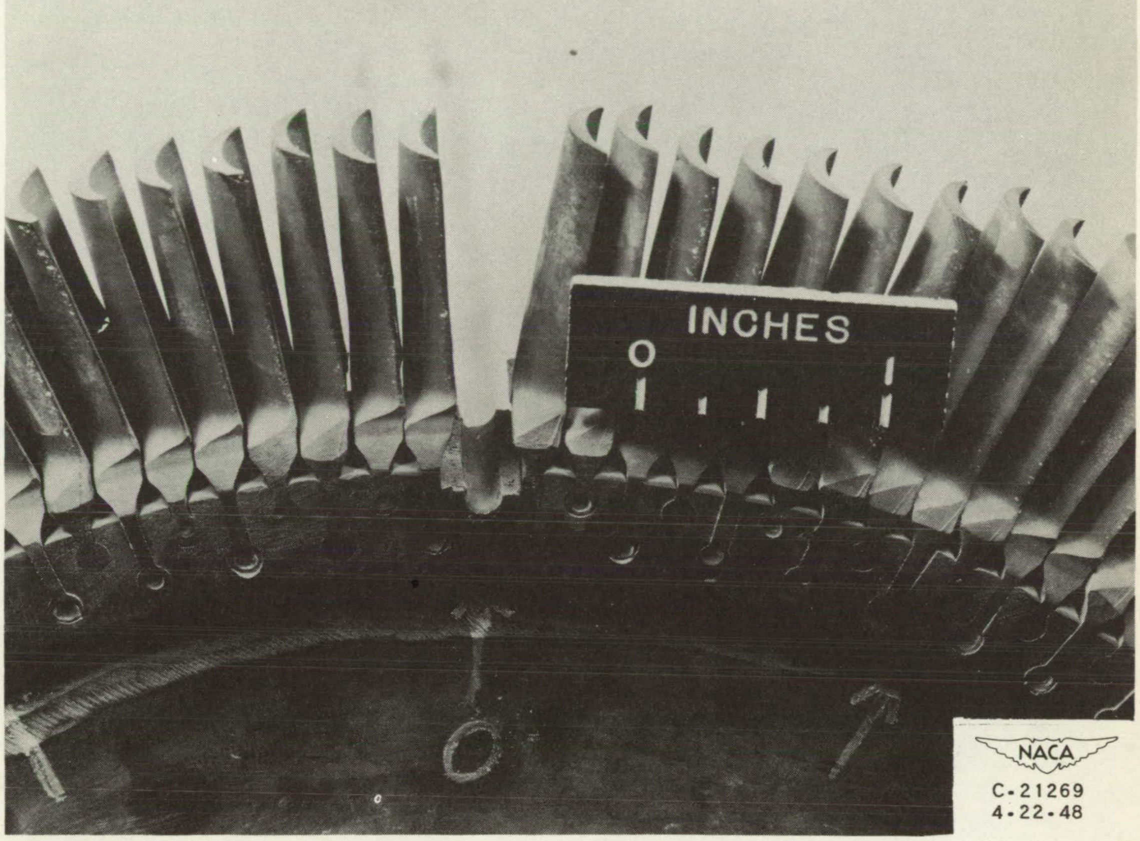

(a) Close-up of failure after 12 hours and 13 minutes of operation.

Figure 12. - Disk-dovetail failure.

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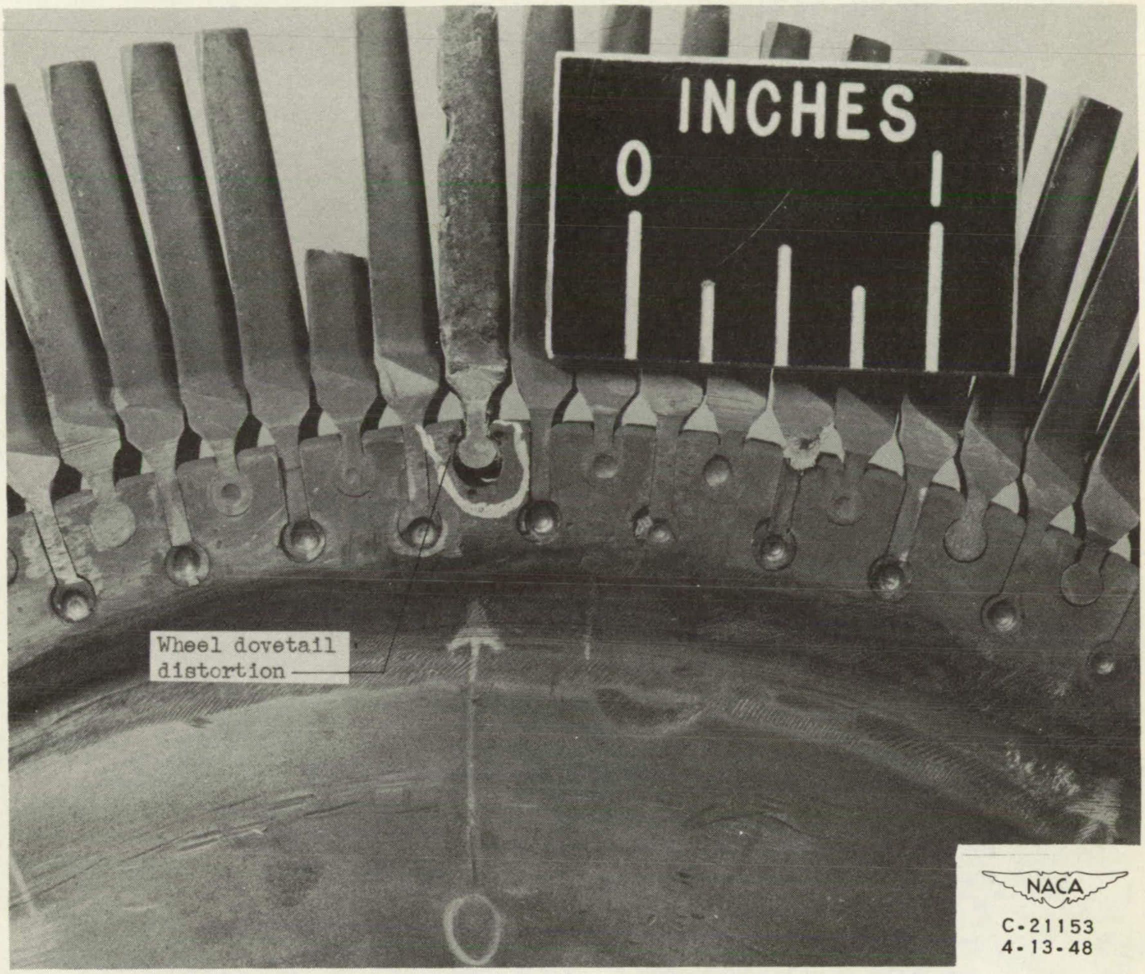

(b) Distortion 33 minutes before failure.

Figure 12. - Concluded. Disk-dovetail failure.

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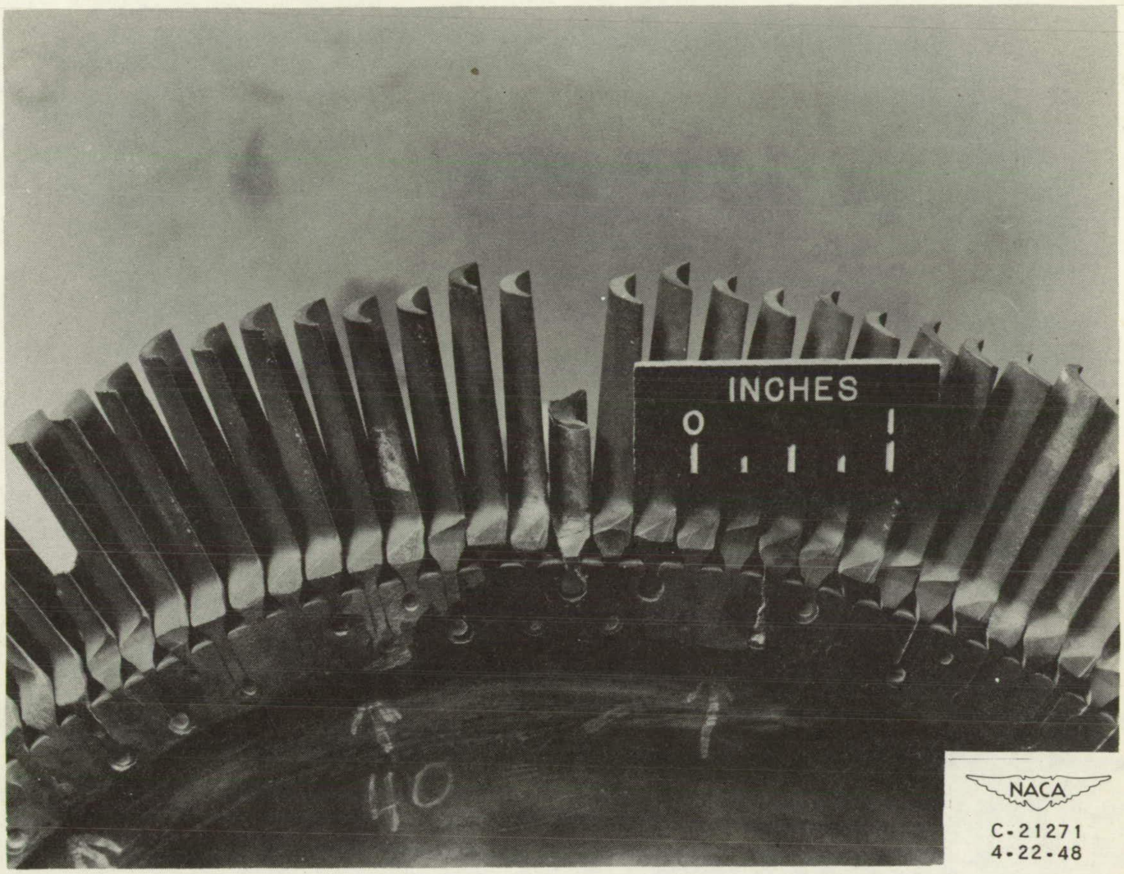

(a) Close-up of failure.

Figure 13. - Ceramal-blade failure after 12 hours and 13 minutes of operation.

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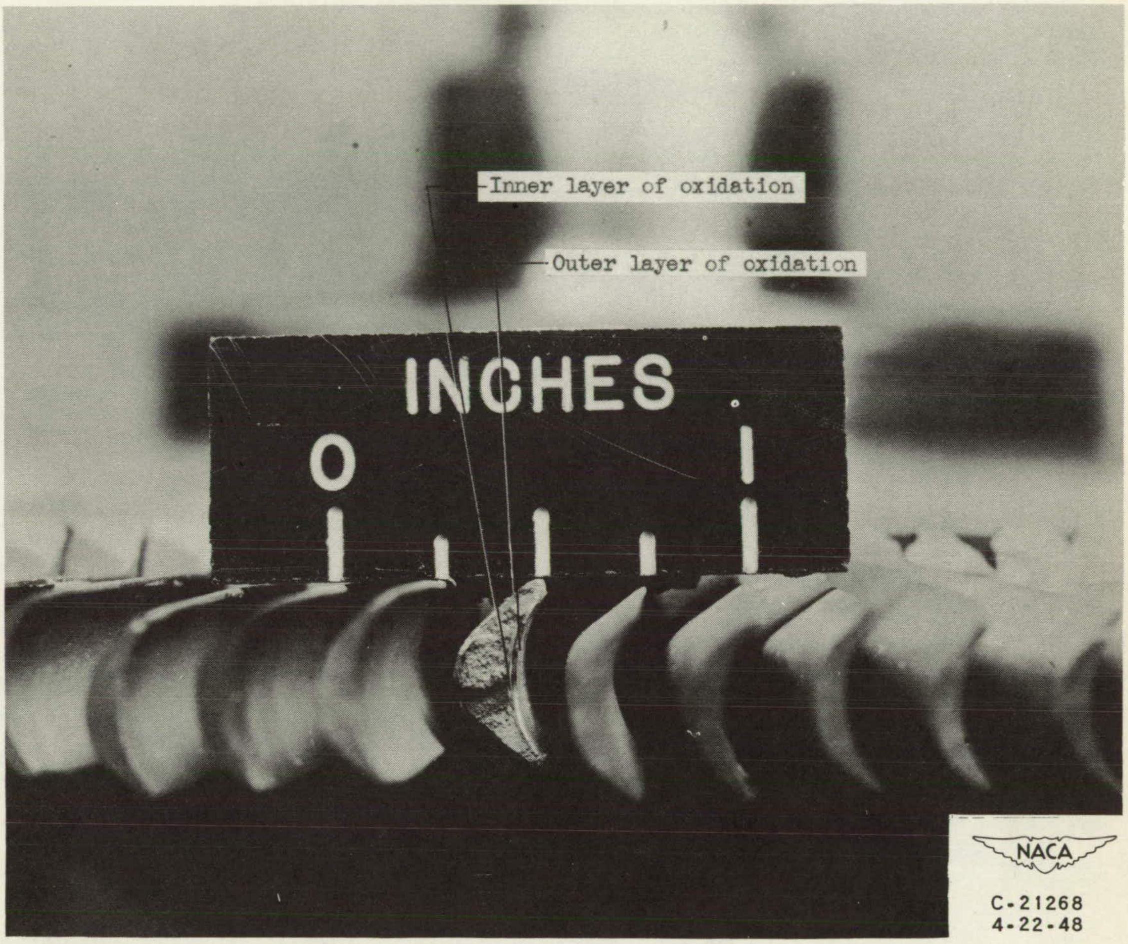

(b) Fractured surface.

Figure 13. - Concluded. Ceramal-blade failure after 12 hours and 13 minutes of operation.